PROJECT SUMMARY

Overview:

The project aims at acquiring an immersive virtual environment that will facilitate ongoing interdisciplinary research in human-machine interaction in dynamic environment at California State University, Long Beach (CSULB). The research team includes twelve faculty members from Computer Engineering & Computer Science, Electrical Engineering, Kinesiology, Mechanical and Aerospace Engineering, Physical Therapy, and Psychology, who have established strong collaboration and common research goals in understanding human motor skills and learning and development of effective assistive technologies to enhance human mobility and function. The proposed instrument is a turnkey, well-integrated immersive virtual reality (VR) environment with synchronized full-body motion tracking. The system includes a four-wall projection system, eight-camera real-time motion capture system, and a control software suite that allows customized software development and additional hardware integration. The VR system provides a cost-effective design solution that can be adapted, utilized, and evaluated to fit the needs of multiple projects relating to human perception as well as human-machine interaction. The flexible usage of the VR environment suits the strong demand to enhance research infrastructure and the use of shared equipment on campus. The system will enable new research activities, teaching opportunities, and enhanced student research training.

Intellectual Merit :

Among the areas of expertise of the research team, the immersive VR system will directly support several research projects relating to human-machine interaction. The research activities are categorized into the following three areas of focus:

Human-robot interaction: understand and model the interaction between human and robot in a dynamic environment in order to develop effective control strategies for single and/or multiple user and robot collaboration

Human performance: study human perception and biomechanics of human movement under various stimuli and develop assistive technologies and/or training protocols to enhance motor skills and learning

Human interaction in complex environment: gain basic understanding and develop metrics for evaluation of human interactions in complex environment that include multisensory feedback, perturbations, advanced modes of display, and multiple users

The research activities will lead to a wide range of applications in rehabilitation, sport training, advanced manufacturing, and overall design of human-machine interfaces.

Broader Impacts :

The acquisition of the VR system will facilitate its usage for research and instruction across multiple disciplines on campus and nearby institutions. Through existing resources and collaboration including the Long Beach VA Medical Center and the CSULB Physical Therapy?s pro brono clinic, the research activities enabled by the instrument have a strong potential for technology transfer that can directly improves the quality of care for individuals in the community and potentially at the regional and national level. CSULB has one of the most diverse student population in the California State University system. Faculty-led multidisciplinary research with modern equipment will directly benefit our students and help to attract and retain underrepresented students. The College of Engineering also offers several outreach programs for which the VR system will be showcased to help attract K-12 and community college students to science and engineering.

3. Project Description

3a. Information about the Proposal

3a1. Instrument Location and Type

Instrument Location: ET-243, California State University Long Beach
Instrument Code: MRI 31-Computation, Visualization, or Database System; Software Instrument

3a2. Justification for Submission as a Development (Track 2) Proposal

N/A

3b. Research Activities to be Enabled

The immersive CAVE Automatic Virtual Environment system will enable a variety of research activities relating to human-machine interaction. This reflects the active research areas carried out by the key personnel and is strongly supported by existing collaboration and resources at the university. The team consists of twelve faculty from multiple departments and colleges at CSULB including the College of Engineering in the Department of Mechanical and Aerospace Engineering (Barjasteh, Demircan, Gao, Marayong, and Shankar), Electrical Engineering (Khoo), and Computer Engineering and Computer Science (Aliasgari), the College of Health and Human Services in the Department of Physical Therapy (Beneck and Krishnan) and Kinesiology (Becker and Wu), and the College of Liberal Arts in the Department of Psychology (Miles). The areas of expertise include robotics and haptics technologies (Marayong), robotics and cooperative control (Shankar), robotics and human biomechanics (Demircan), control systems (Gao), material sciences (Barjasteh), mechatronics and signal processing (Khoo), cryptography and information security (Aliasgari), biomechanics (Becker), orthopedic physical therapy (Beneck), posture and gait rehabilitation (Krishnan), motor learning (Wu), and cognition and human factors (Miles). The research activities that enhance the development of technology for effective human-machine interaction in dynamic environments are categorized into three focus areas:

- Human-robot interaction
- Human motor learning and performance
- Human interaction in complex systems

The following description provides the details of collaborative research activities, involved personnel, and existing infrastructure to support full usage of the proposed system. The table below summarizes the research areas, associated projects and the lead personnel in the respective areas.

Research Areas	**Sub-areas**	**Personnel (arranged by alphabetical order)**
Human-robot interaction	Rehabilitation	Emel Demircan (co-PI) Vennila Krishnan (co-PI) Panadda Marayong (PI)
	Advanced manufacturing	Ehsan Barjasteh (Faculty associate) Praveen Shankar (co-PI)
Human motor	Rehabilitation	James Becker (Faculty associate)

learning and performance		Emel Demircan (co-PI) I-Hung Khoo (Faculty associate) Vennila Krishnan (co-PI) Panadda Marayong (PI) Will Wu (co-PI)
	Sport training	James Becker (Faculty associate) George Beneck (Faculty associate) Will Wu (co-PI)
	Musculoskeletal modelling	James Becker (Faculty associate) Emel Demircan (co-PI)
Human interaction in complex systems	Human movement and perception	James Becker (Faculty associate) Jim Miles (Faculty associate) Will Wu (co-PI)
	Intelligent cockpit	Mehrdad Aliasgari (Faculty associate) Qingbin Gao (Faculty associate) Panadda Marayong (PI) Jim Miles (Faculty associate) Praveen Shankar (co-PI)

Table 3.1: Summary of Personnel by Proposed Research Area

Area 1: Human-Robot Interaction

The research in this area focuses on the use of the CAVE environment in studying the interaction between human and robot in a dynamic environment in order to develop effective control strategies for single and/or multiple user and robot collaboration. The applications cover two primary areas: rehabilitation and advanced manufacturing.

<u>Rehabilitation</u>: Dr. Emel Demircan, the head of the Human Performance and Robotics Laboratory (HPRL) within the Department of Mechanical and Aerospace Engineering, will lead the research in human-robot interaction for rehabilitation. The dynamic immersive system will enable the use of 3D virtual environments together with the robotic platform that already exists in HPRL. The 6-degrees of freedom device is a lightweight, torque controlled robotic arm mainly used for physical assistance and motion guidance. This platform together with the virtual immersive environment will provide the monitoring, analysis and prediction of human subjects motions in real-time. This research area will capitalize on the synergy between robotics and biomechanics for modeling the dynamics and simulating the motion of humans. By combining advanced robotics control methods with dynamically consistent computational musculoskeletal models, controlled simulations of fully dynamic neuro-musculoskeletal models will be enabled. This opens up the possibility of quantitative prediction of subject-specific response to proposed training interventions by incorporating a model of the central nervous system (CNS) behavior and consequent change in control signals. In addition, these systems will include computational techniques from robotics that enable real-time response to produce a physiologically meaningful interactive simulation of controlled human motion.

In the context of rehabilitation, the technologies developed throughout this work would allow physical therapists to verify in detail whether certain exercises will have the desired effect, even in the presence of abnormal neuro-musculoskeletal characteristics, or to pinpoint groups of muscles that should be strengthened in order to alleviate a given set of symptoms. Another possibility is to use real-time motion analysis and biofeedback to correct a subject's movement in order to minimize joint stresses (thus forestalling overuse injuries), reduce the risk of re-injuries, or maximize sports performance. While sport training requires optimizing motor abilities, rehabilitation requires either substituting for lost motor ability or changing motor profiles to suit clinical goals. Pilot studies relying on recent advances in robotic dynamics analysis and haptic feedback methods have succeeded in retraining a subject's walking gait to alter loads on some lower limb joints (i.e., knee, ankle). The framework developed within this work would allow generalizing this technique to other motions and multiple joints. Current technologies do not permit detailed motion reconstruction in real-time, limiting their use in clinical settings. The real-time capabilities to be developed during this project will allow immediate and effective dynamic feedback during task performance.

Advanced Manufacturing: The usage of the CAVE system in the area of manufacturing will be conducted through Dr. Praveen Shankar's Collaborative Autonomous Systems Laboratory (CASL). The objective of this research is to implement and test reconfigurable strategies for controlling multiple manufacturing robots in collaboration with a human operator [Maeda, 2001; Liu, 2014] in an uncertain dynamic environment. The proposed approach involves utilizing a hierarchical control architecture that incorporates a global motion planning algorithm which can track the human as well as robot motion while supervising the local control algorithm for individual robots (Figure 3.1). The primary usage of the immersive virtual environment and the motion capture system in this research is the ability to simulate either the human operator or the manufacturing robots while the other actively interacts with the simulation. Such a setup will allow the testing of multiple motion planning and control algorithms within a relatively safe operating environment for the human. Secondly, this setup will permit the accurate measurement of the human movement using the motion capture system that can be utilized for accurately modeling the motion of a human operator in the manufacturing environment with respect to specific tasks. The CASL lab hosts multiple robotic systems including ground rovers, underwater vehicles, rotary and fixed wing aerial vehicles and advanced 6-DOF manufacturing robotic manipulators including 2 DENSO VP6242 robots and the new Rethink Robotics Baxter two armed robots. Both these robots are situated on movable platforms and can easily be relocated to the immersive virtual environment for testing purposes.

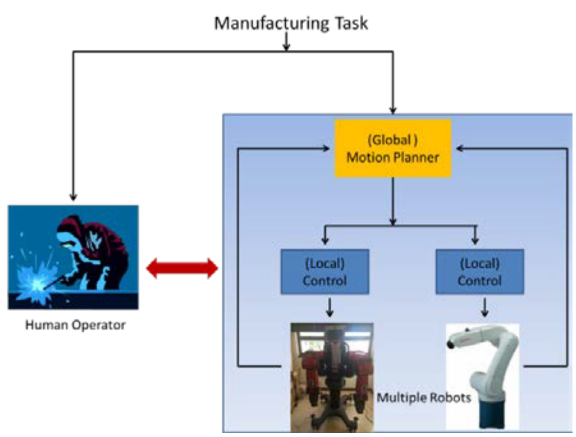

Figure 3.1: Human-robot interaction in manufacturing

Area 2: Human Motor Learning and Performance

The CSULB Department of Physical Therapy (PT) established multiple rehabilitation and training programs that serve the local community. The PT Department offers Neurology Pro Bono Clinic and PT @ the Beach Physical Therapy Faculty Practice that provide clinical evaluation and treatment of movement dysfunction for patients in the community as well as within the CSU, Long Beach campus. Outside of CSULB, the senior personnel also establish a strong collaboration with prosthetics clinic at the Long Beach VA Medical Center (see Letter of Collaboration from Dana Craig, Director of the Motion and Gait Analysis Lab, Long Beach VA). The available resources and patient population has led to several collaborative projects involving development of technologies to enhance human motor skills and performance (Figure 3.2).

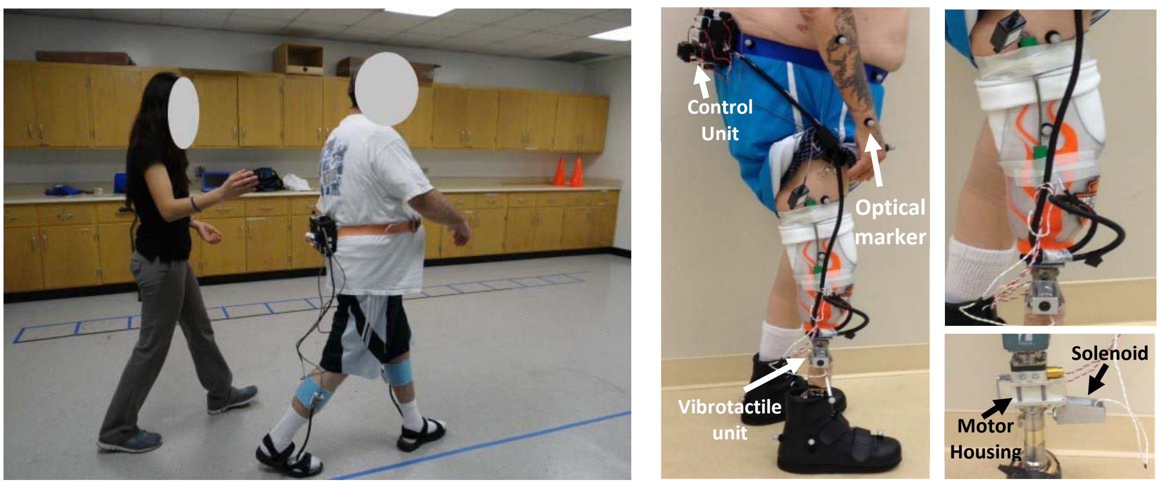

Figure 3.2: (left) User experiment with the Walk-Even device for gait training for post-stroke survivors from CSULB Physical Therapy's Pro Brono Clinic (right) vibrotactile device for gait rehabilitation of individuals with lower-limb amputation at the Long Beach VA.

Rehabilitation: The use of virtual immersion is widely recognized in the field of rehabilitation and physical therapy to improve patient's functional abilities. An advantage of an immersive virtual reality is that it could enable patients to practice intensively in a much more motivating and engaging way than the conventional exercise, which can sometimes be tedious. Additionally the simulation can be altered to accommodate different training scenarios in a convenient and cost effective way. Stroke rehabilitation is an area of active research collaboration between the senior personnel, I-Hung Khoo (Director of the Circuit Design and FPGA Laboratory), Vennila Krishnan (Director of the Clinical Rehabilitation And Biomechanics (CRAB) Laboratory and Faculty associate of the Physical Therapy's Pro Brono Clinic), and Panadda Marayong (Director of the Robotics and Interactive Systems Engineering Laboratory). Stroke is one of the leading causes of death and disability worldwide [Feigin, 2009]. Post-stroke, individuals often demonstrate asymmetry in body postures and weight distributions resulting in asymmetrical gait patterns with the characteristic presentation of prolonged swing time on the paretic limb. Past studies show that only 7% of individuals with chronic stroke resume functional activities in the home and community [Goldie 1996; Park 2011]. To aim for an eventual community participation for the individuals with chronic stroke, treatment approach should not only concentrate on gaining the strength and function, but should also take into account of varied environmental factors in which the treatment is provided, so that transfer of the gain to community participation is obtained in parallel. The common environmental factors include different terrain characteristics, traffic level, and outdoor settings, thus simulating a natural environment in which the treatment is provided, rather than performing in a clinical or hospital-based settings. The group has developed a feedback device, called Walk-Even, that provides real-time gait measurement, asymmetry detection, and audio and tactile feedback for post-stroke rehabilitation [Khoo, 2015; Rojas, 2015; Krishnan, 2015]. Integration of the Walk-Even device in the CAVE environment will provide auditory, visual, and proprioceptive feedback in real-time in an environment that simulate real-life conditions. Additionally, the CAVE environment can be customized to individual needs for training environment and the difficulty of the exercise can be tailored to the individual's level of adaptation. The CAVE system can create a stimulating environment that can be tuned to produce active, high-intensity, repetitive and task-oriented movements that can significantly enhance motor learning in such population.

An additional use the immersive virtual reality (VR) in enhancing human performance relates to another collaborative research on motor learning and development of rehabilitation technologies for persons with lower-limb amputation (Marayong, Khoo, Wu, Becker). Individuals with lower-limb amputation (LLA) typically experience reduced mobility and stability due to the loss of exteroceptive and proprioceptive information that enable the perception of limb's position or movement in space [Doubler, 1984]. To maintain posture and effectively ambulate in complex environment, individuals with LLA rely on multiple sensory feedbacks, including visual, audio, and haptic feedback. While recent advances in artificial limbs with sensory feedback have helped to restore some important functionality, these systems required specialized and costly hardware [Clippinger, 1982; Fan, 2008; Kaczmarek, 1991; Kalkade, 2003; Yoshida, 1996; Zambarbieri, 2001]. More importantly, there still exists a gap in the understanding of how individuals with LLA perceive and respond to these stimuli, especially in a dynamic real-life environment that demands moderate to high level of situation awareness and multiple sensory information. In collaboration with the clinicians at the Long Beach VA Medical Center, the team has developed a low-cost vibrotactile device that can be fitted onto a standard prosthesis to enhance proprioception and can be used for motor learning research and rehabilitation training for individuals with transtibial amputation [Marayong, 2014]. The system consists of a vibrotactile feedback unit, inertial measurement units (IMUs), and a control interface. The device generates tactile feedback through the prosthesis during a specified phase in the gait to simulate a real-life perturbation. The work also includes a motor learning study to investigate the effect of internal and external focus of attention cues, provided as verbal instructions, which are specific to enhancing the stability of persons with amputation while using the vibrotactile device. Initial results collected from two individuals with below-knee amputation performing a normal walk in a lab setting indicates the effectiveness of the training in increasing the number of corrective movements after a perturbation [Rivera, 2015]. The acquired system with motion tracking will enable the extension of this research to investigate the effectiveness of artificial feedback on motor learning and rehabilitative outcome in VR environment that mimics real indoor/outdoor scenes. Various simulated environments with coordinated visual, audio and haptic cues will be created to study the effect and interaction of multiple modes of sensory feedback on the motor learning outcome in individuals with LLA.

Sport Training: The CAVE system will be used to create realistic environment to conduct movement research for sport training. One of research projects that will be enabled by the system is the study of mechanics of throwing a football in quarterbacks (Beneck). One of the successful characteristics of a quarterback is how quickly does the football leave his hand after deciding to throw to a particular receiver. The less time used by the quarterback to release the football limits the time for defenders to alter their defense strategy in response to the quarterback's decision thus improving the chance that the pass will be completed. However, while the mechanics of a baseball pitch has been studied in detail [Shimamura, 2015; Ramsey, 2014; Oyama, 2013; Grantham, 2014; Fleisig, 2011], little is known about the throwing mechanics and physical characteristics associated with a quick release exhibited by quarterbacks [Escamilla, 2009]. Pitching a baseball involves a windup and accentuated cocking phase to use potential and kinetic energy to accelerate the ball [Konda, 2015]. Because of the importance of minimizing the release time, a quarterback spontaneously throws without a windup and uses a diminished cocking phase to complete a pass. In those quarterbacks with a quicker release, the cocking phase appears further diminished with an apparent greater synchronization of trunk rotation with shoulder kinematics. To examine the kinematics associated with a quick release throw, the CAVE system will be used to simulate a competitive football environment to enable throwing scenarios where quick responses by the quarterback are necessary. High school quarterbacks in the Long Beach, CA and surrounding area will be invited to participate in the study. Throwing kinematics, kinetics, temporal characteristics and electromyographic data of the trunk and shoulder will be collected from the motion capture and EMG system for comparison. A better understanding of the mechanics of throwing a football with a quick release and the differences in muscle activation and strength between throwers with and without a quick release will enable coaches to teach and train these mechanics in future quarterbacks.

Musculoskeletal Modeling: Musculoskeletal modeling and motion analysis have tremendous potential to improve quality of life by elucidating cause and effect relationships in individuals with movement disorders and by predicting effective surgical and rehabilitative treatments. To apply this technology and to evaluate treatments, we need human musculoskeletal models and simulations that accurately reproduce movement dynamics in real-time. For the proposed research area, a system that includes real-time interpretation of the movements and prediction of movement patterns that may result in short or long-term impairment in human performance will be developed. In order to characterize muscle function and dynamics during human performance, the dynamic immersive CAVE system will be used to analyze human dynamic motions in the presence of contacts and additional constraints. The control formulation developed by Dr. Demircan for constraint-consistent synthesis of human whole-body motions [Demircan, 2012] will be the basis of motion synthesis and analysis. This method provides a unique understanding of the basis of human movement and can be efficiently applied for analyzing or predicting dysfunction and pathology in human locomotion (Figure 3.3). In addition, the EMG-informed Computed Muscle Control technique [Demircan, 2009] for resolving muscle redundancies will be used together with the three-dimensional virtual environment to provide robust estimates of muscle activation patterns based on both filtered EMG data and the computed muscle control. This method is already implemented in OpenSim [Delp, 2007], and will help create dynamic simulations of normal and pathological movement.

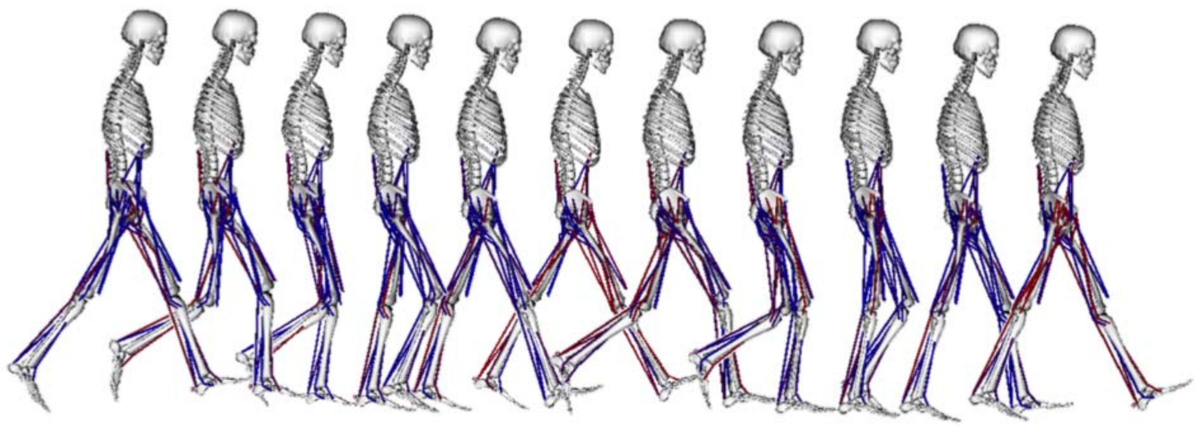

Figure 3.3: Three-dimensional dynamic simulation of human gait. The lower extremity and the back joint are actuated by 54 musculo-tendon actuators. Muscle color indicates simulated activation level from fully activated (red) to fully deactivated (blue).

Area 3: Human Interaction in Complex Systems

The research proposed in this area focus on gaining basic understanding and develop metrics for evaluation of various aspects of human interactions in complex systems, which embody multiple sensory feedback, perturbations, advanced modes of display, and multiple users. The results of research activities in this area will enhance the development of human-machine technologies that are discussed in Area 1 and 2.

<u>Human Movement and Perception</u>: The research activities in these sub-areas involve two categories, one that involves the study of the effect of perception on movement and the other on the effect of physical state and movement on human attention and perception.

Perceptual contributions to human movement: Relevant to the technology for rehabilitation and sport training, people generate movements within their environments in different ways whether the individual is disabled or not, fit like an athlete or out of shape due to a sedentary lifestyle. The difference in movement strategies is largely impacted by the way human sense, interpret, and perceive their environment. Understanding the link between perception and action can help scientists and practitioners better facilitate environments to improved performance that ranges from winning a championship in a sport to navigating safely while grocery shopping. The important aspect to achieve sport success or a healthy lifestyle is to better understand how humans perceive their environment based on the physical constraints around them and the constraints of their physical and cognitive abilities. A CAVE system will better allow for the investigation of identifying the complex interaction between individuals and their environment. This system will help research team systematically investigate how changes in one's environment have an effect on their ability to move safely within it. Utilizing this technology will allow researchers to design environments for older adults trying to walk or fall safely, athletes anticipate information rich visual cues that lead to enhanced performance, or disabled individuals and how they make movement choices based on their disability. A virtual system paired with conventional equipment for analyzing movements such as EMG, three-dimensional motion capture, force plates, and electromyography will allow researchers not only

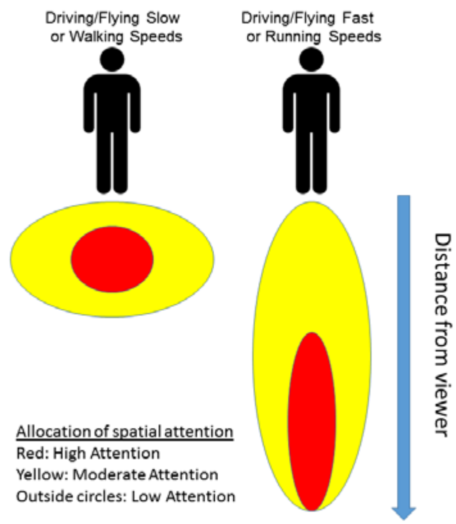

Figure 3.4: Hypothesized changes in how spatial attention is allocated in a 3-d environment when moving at slow or fast apparent speeds

a detail method of studying human movement but also a flexible system in which people of all ages, disabilities, and ability levels can be safely challenged in multiple real-world environments.

The influence of physical state on attention and perception of the environment: It is well understood that the location of body parts and movement of the body strongly influence where human focus of our limited attentional resources within the environment. In general, our attention is gradated as distance increases [Anderson, 1993]. However, dynamic movement changes how human allocate this attention. For example, when moving at different speeds (e.g., walking or driving a car), attention is directed at different distances in anticipation of avoiding future obstacles [Kimura, 2009] and greater attention is allocated around the hand to ready the perceptual system for manual interaction [Reed, 2006]. Additionally, individuals with mobility issues or lower levels of experience in an automobile or aircraft may expend increased attentional resources at safely moving through the immediately local environment with a cost to recognizing unexpected obstacle or dangers in the extended environment. Thus, it is paramount not only to understand how perceptual information influences our actions, but also how our current and anticipated actions influence perception of the environment through the focus of attention.

Due to the difficulty in measuring attention when dynamically interacting with the 3D environment, most extant research has been limited to measuring attention through target detection on simple 2D displays and with only rudimentary body movements such as arm reaching, which reduces the ecological validity of the results. The proposed system will allow for attention to be measured during ongoing body movements and perceived movement in conveyances such as simulated driving. In particular, an interactive VR system allows targets to be presented at specific locations in the environment based on the state of the body. While standing still, walking, running, and sitting in a simulated car or aircraft cockpit, participants will be instructed to respond when a unique target is presented in the environment. By measuring the accuracy and duration required to detect targets at various locations and distances in the environment in relation to an individual, it is possible to create a model of how spatial attention is allocated in 3d space. Additionally, by systematically varying the apparent speed at which the environment appears to move around an individual (i.e., walking vs. running; driving and flying at low vs. high velocities), a dynamic heat map of attention can then be developed similar to the hypothesized data in Figure 3.4. In this figure, attention is highest in the red areas of space, lower in the yellow areas, and very low outside these areas. Note that the apparent speed of the individual changes how attention is focused in the environment. This information would provide invaluable information for the design of vehicles as well as determine specific strategies to improve mobility in individuals with varied abilities to walk, run, or drive cars and pilot aircraft by training them to better focus attention on critical dangers in the environment. Furthermore, this information can be used to determine individual differences in how dynamic spatial attention is allocated that are related to physical fitness, age, and previous experience.

<u>Intelligent Cockpit</u>: This project focuses on the development and evaluation of technologies associated with the intelligent cockpit of a next generation civilian and military aircraft. It is anticipated that airplane cockpits of the future will be intelligent enough to share routine as well as expert tasks of the pilot, particularly to relieve fatigue and improve overall performance. For military aircraft, the pilot is expected to be more involved in the management of multiple networked resources than in active combat. Such an environment will benefit greatly from in-cockpit automated assistant systems that reduce pilot workload and increase their performance. However, such systems will need an intuitive and trusted interface to present information to and interact with pilots. The objective of this research is to understand and measure the effectiveness of novel interfaces like haptic devices [Park, 2013; Rorie 2012] and as yet untested sources of information such as holographic images on pilot performance in an intelligent cockpit. Through a joint project (Shankar and Aliasgari) with the Dean of College of Engineering as PI, an experimental setup that utilizes a modified F-5 military aircraft cockpit was developed to understand how multiple sources of information affects the performance of a pilot in conducting routine aircraft maneuvers. The primary goal is to develop a universal metric that can be utilized to understand the impact of novel interfaces in the performance of the pilot. Current research has focused on visual sources of information that can be classified either as distractions or analytical tasks using data collected from about 30 subjects. The primary requirement of the CAVE environment to further this research is to simulate varying flight scenarios that are limited to 2D simulations in the current setup (Figure 3.5). In addition, the virtual environment can be utilized to quickly configure and implement new sources of information and tasks to the pilot. Further, the motion capture system can simulate the head tracking system in addition to providing more information about the limb movement of the pilot. With the existing collaboration with the Human Factors Program in the CSULB Psychology Department (Marayong and Miles), the research activities will extend to human factors analysis and design for systems with multisensory feedback including visual, audio, and haptic information (see letter of collaboration from Dr. Kim P. L. Vu).

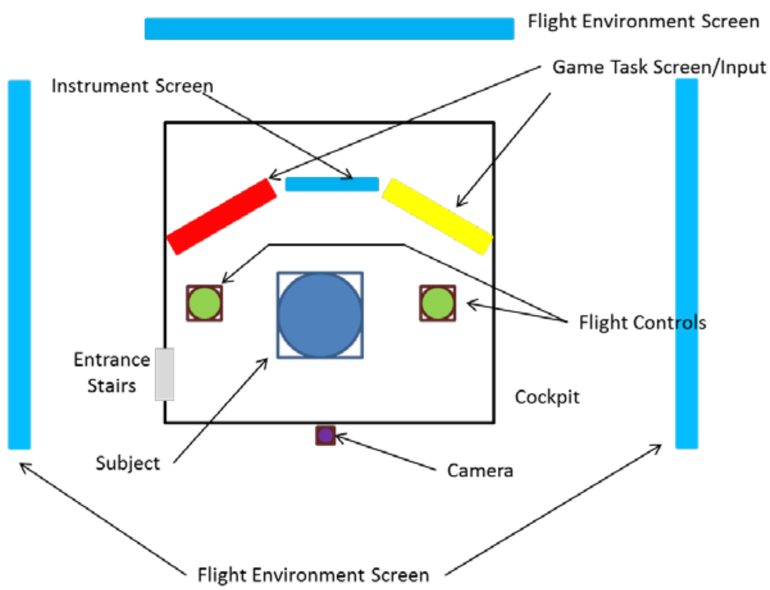

Figure 3.5: Current 2D cockpit experiment setup

3c. Description of the Research Instrument and Needs

The research instrument to enable our common research activities is a CAVE automatic virtual reality environment. The system consists of multiple large screens that incorporate real-time head and body tracking to generate room-sized 3D display that can be viewed by multiple users for shared VR experience. While multiple vendors offer CAVE systems, the VisCube M4+ by VisBox, Inc. (Saint Joseph, IL) is selected based on its features and competitive pricing. The M4+ system (Figure 3.6) consists of front-projected four panel displays (three walls and a floor), body tracking system and graphics workstation. The system specifications are provided in Table 3.2. The screens are customized to fit the room space that is allocated by the College of Engineering (see letter of support from Dr. Hamid Rahai, College of Engineering Associate Dean of Research and Graduate Programs). The M4+ system has a portable design that can be easily disassembled, moved, and reassembled to allow addition and removal of other equipment, such as the modified F-5 cockpit, robots, input console, and instrumented treadmill, required by different research activities described in Section 3b. Using virtual reality, rare and complex scenarios can be simulated, allowing a user to build the necessary skills and abilities before engaging in the task in real life. By providing a highly realistic simulation using the CAVE system, training scenarios that are not safe, controllable, or possible in the real world can be practiced, allowing users to develop the confidence and skill to face the real-world tasks. In addition, users can get immediate feedback on their performance and visualize their actions from multiple viewpoints and angles

The enhanced motion capture system (ARTTrack5) with full body and finger tracking system with eight infrared optical cameras is required by the workspace volume and the resolution needed for research related to biomechanics and human motor control. The cameras work with passive or active markers. The finger-tracking system capable of 3 finger tracking will be needed in human-computer and human-machine research activities. A high frame rate (up to 300 Hz) is necessary for research activities involving sports training. The ART cameras will be ceiling mounted. The tracking system components are shown in Figure 3.7. All of the system components are fully integrated as a turn-key system and are supported by an open source software that allows integration of additional hardware, such as a commercial haptic interfaces and robotic devices, and software development in the future. There is no similar system available on campus or accessible in nearby institutions. The CAVE system will modernize the research facilities and enable multidisciplinary research activities that are currently limited by the existing infrastructure. New areas of research and curriculum development can be developed to enhance teaching and research training opportunities for undergraduate and graduate students at the university.

Components	**Specifications**
Center and floor projector	1920 x 1200 resolution per surface area
Side wall projector	1316 x 1200 resolution per surface area
Approximate footprint	12'w x 8.5'd x 10'h
ARTTRACK5 full body tracking system with passive markers	8 infrared optical 6-DOF tracking cameras, sensor resolution of 1.3 megapixels at full frame mode, frame rate up to 300 Hz
ART Fingertracking	Frame rate: hand target at 60 Hz and 3-finger thimbles at 20 Hz. Battery-operated (Li-Ion battery 3.7V, 700 mAh)
Audio system	Yamaha RX-V377 5.1 receiver and Leviton AEH50-BL 5.1 speaker system
Operating system and software	Windows and/or Linux with open VR libraries

Table 3.2: VisCube M4+ system specifications

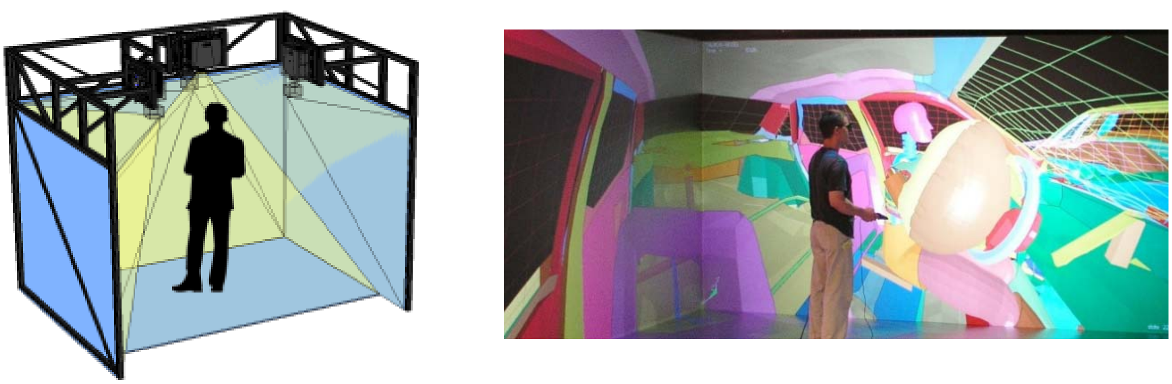

Figure 3.6: VisCube M4+ system with example immersive environment (sources: VisBox, Inc.)